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Review and Evaluation of Wireless Power Transfer (WPT) for Electric Transit Applications

AUGUST 2014

FTA Report No. 0060
Federal Transit Administration

PREPARED BY

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U. S. Department of Transportation
Volpe National Transportation Systems Center

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Federal Transit Administration

COVER PHOTO

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT

This research report provides a status review of emerging and existing Wireless Power Transfer (WPT) technologies applicable to electric bus (EB) and rail transit. The WPT technology options discussed, especially Inductive Power Transfer (IPT), enable rapid in-station or opportunity (boost) dynamic recharging of electric bus batteries for range extension and promise economic, convenience, and safety benefits. Based on a comprehensive literature review, international and U.S. WPT bus and light rail systems deployed, demonstrated, or planned are described, noting their respective providers, system specifications and attributes, and Technology Readiness Level (TRL). FTA-funded WPT demonstrations currently underway or planned are also highlighted. Industry technical and safety standards (frequency, power, and interoperability) are currently in development. Regulations and consensus standards for emissions and human exposure safety to electromagnetic radiation and fields (EMR/EMF) and protection from electromagnetic Interference (EMI) are reviewed. Measured EMR/EMR levels for various WPT electric bus systems comply with applicable occupational and public safety, health, and environmental exposure standards. Information on the cost-benefit, reliability, durability, and safety of WPT infrastructure and vehicle systems is scant. Research gaps, as well as challenges and opportunities for WPT commercial deployment, are identified.

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ABSTRACT

This research report provides a status review of emerging and existing Wireless Power Transfer (WPT) technologies applicable to electric bus (EB) and rail transit. The WPT technology options discussed, especially Inductive Power Transfer (IPT), enable rapid in-station or opportunity (boost) dynamic recharging of electric bus batteries for range extension. In addition, WPT technology offers the promise of economic benefits, greater convenience, and safety benefits. IPT is a subset of technologies beneath the WPT umbrella in which there is resonant inductive electromagnetic power transfer across an air gap. IPT is also the most widely used of the WPT technologies and is based on a changing magnetic field produced by alternating currents in the primary coil, inducing a voltage and current in a secondary coil across an air gap. Based on a comprehensive literature review, international and U.S. WPT bus and light rail systems that have been deployed, demonstrated, or are planned are described. These descriptions note their respective providers, system specifications and attributes, and Technology Readiness Level (TRL). FTA-funded WPT demonstrations currently underway or planned are also highlighted. Industry technical and safety standards (e.g., for frequency, power, and interoperability) are currently in development. Regulations and consensus standards for emissions and human exposure safety to electromagnetic radiation and fields (EMR/EMF) and protection from electromagnetic Interference (EMI) are reviewed. The measured EMR/EMF levels for various WPT electric bus systems comply with applicable occupational and public safety, health, and environmental exposure standards. Information on the cost-benefit, reliability, durability, and safety of WPT infrastructure and vehicle systems is limited. As a result, this research report identifies research gaps, as well as challenges and opportunities, for WPT commercial deployment.

EXECUTIVE SUMMARY

This report provides a status review of emerging and existing Wireless Power Transfer (WPT) technologies applicable to electric bus (EB) and rail transit. WPT technology options discussed, especially the most widely used subset of WPT known as Inductive Power Transfer (IPT), enable rapid in-station or opportunity (boost) dynamic recharging of electric bus batteries for range extension. In addition, WPT technology offers the promise of economic benefits, greater convenience, safety benefits, and environmental sustainability benefits.

Section 2 identifies commercial WPT technology developers and providers of Electric Vehicle Supply Equipment (EVSE) infrastructure as well as vehicle modules for bus and rail systems. Ongoing research and development efforts at federal agencies to improve WPT vehicle technologies are also described.

In Section 3, based on a comprehensive literature review, international and U.S. bus and rail projects that use diverse WPT technology options are presented. These WPT projects vary in scope from the evaluation phase to the demonstration and operational phases. FTA-funded WPT demonstrations currently underway or planned are also highlighted.

Section 4 highlights the Safety, Health, and Environmental (SHE) issues associated with WPT infrastructure and vehicles operation, as well as the applicable regulations and voluntary technical and safety standards. FCC regulations, as well as voluntary technical and safety standards, are currently in development for WPT specifications, such as system frequency, power, field and radiation emissions, and interoperability. Regulations and consensus standards are reviewed that limit the electromagnetic radiation and fields (EMR/EMF) emissions for human exposure safety assurance. Standards for protection of electrical equipment and electronic devices from electromagnetic Interference (EMI) to ensure electromagnetic compatibility (EMC) are also reviewed. Measured EMR/EMF levels for various WPT electric bus systems demonstrated to date comply with these applicable occupational and public safety, health, and environmental exposure standards.

In Section 5, the Technology Readiness Level (TRL) is assessed for WPT transit systems already deployed, demonstrated, or in the developmental phase. Knowledge gaps, research needs, and major challenges to deployment of WPT in transit are noted. Information on the cost-benefit, reliability, durability, and safety of WPT infrastructure and vehicle systems is limited. The research gaps, as well as challenges and opportunities for WPT commercial transit systems deployment, are also identified, discussed, and summarized. Competing WPT technology options promise to improve electric bus mobility, logistics, and user convenience through shorter station dwell times for recharging electric bus batteries. Potential advantages of WPT technologies include interoperability, ease-of-use, and environmental sustainability, as well as lower lifecycle cost and higher energy efficiency than conventional wired alternatives. WPT could also reduce

vehicle cost by allowing for smaller, lighter, and lower capacity batteries. WPT technologies could also improve system operational safety, since road-embedded infrastructure has no exposed high voltage cables or power outlets for plug-in hybrid and electric buses. However, potential WPT benefits, such as the cost of infrastructure construction, operation, and maintenance, as well as reliability and durability, must first be quantified for in-service operation for adoption by transit agencies. FTA-funded WPT bus projects will address key knowledge gaps. In-service testing of competing WPT options for electric bus and rail applications and quantitative data on WPT economic, safety, reliability, and potential benefits are needed to overcome barriers to widespread commercialization and public transit implementation.

SECTION

1

Background and Promise of WPT Technologies

Recent American Public Transportation Association (APTA) trends and statistics[1] regarding public transit adoption of advanced technologies and fuels show that more than 35 percent of public transit buses in 2011 featured advanced power-train technologies (all-electric, hybrid, fuel cell) and/or used cleaner alternative fuels (natural gas, propane, biodiesel). This report provides a status review of several emerging Wireless Power Transfer (WPT) technology options for dynamic or stationary charging for electric bus (EB) batteries and rail transit vehicles that promise further advances.

This report is intended to review the status of wireless charging options for electric bus and rail transit vehicles and to explore challenges to and promising opportunities for WPT deployment. Knowledge gaps and research needs that could be addressed by near-term Federal Transit Administration (FTA) Research, Development, and Technology Demonstration Test and Evaluation (RDT&E) are identified. Recent presentations by the FTA Office of Mobility Innovation[2] have highlighted advanced transit bus and light rail vehicles (LRV) concepts with diverse energy storage, traction power, and propulsion technologies. Several multi-year Transit Investments in Greenhouse Gas and Energy Reduction (TIGGER)[3] and the Clean Fuels[4] Program awards are intended to demonstrate alternative WPT technology applications. Funded projects for rapid WPT recharge of electric bus batteries include:

- University of Utah Wireless Advanced Vehicle Electrification (WAVE) technology featured in the campus Aggie bus, and the large bus with the Utah Transit Authority.
- Proposed McAllen, Texas, proposed WAVE WPT implementation.
- Howard County Transit Authority electric bus retrofit in Baltimore (WAVE under consideration).
- Additional WPT transit projects funded by Clean Bus/Clean Fuels grants.

The Wireless Power Consortium has posted comprehensive information on the principles, technology options, and advantages of WPT.[5] Inductive Power Transfer (IPT) is a special category of WPT that exploits basic laws of physics,[6] including:

- A wire carrying an electric current produces a magnetic field around the wire (Ampere's Law).
- A coil intersecting a magnetic field produces a voltage in that coil (Faraday's Law).

- Electromagnetic power transfer between electrical circuits across an air gap can be achieved using magnetic field coupling at resonance (Tesla).

Currently, wired chargers operate with total system efficiency of 50–70 percent from the alternating current (AC) wall socket to the device battery, due to losses in inverters and rectifiers, transformers, electronics, components, and distribution.[7] In contrast to conventional or wired conductive contact in recharging EB batteries, WPT promises improved speed, convenience, safety, and environmental benefits for a broad range of commercial applications, at comparable or better efficiency. WPT technologies could extend the range of electric buses and LRVs through either dynamic opportunity (or boost) charging while moving over roadway charger plates or during station stops.

WPT technology developers and providers of Electric Vehicle Supply Equipment (EVSE) infrastructure and bus and rail vehicle systems are identified in Section 2.

Section 3 presents illustrative bus, tram, and light rail WPT projects from international and U.S. demonstrations and evaluations. If verified and validated for in-service transit operations, the WPT options discussed in Section 2 could improve electric bus mobility, logistics, and user convenience through shorter station dwell times for recharge. WPT could also reduce vehicle cost by allowing for smaller, lighter, and lower capacity batteries. Assuming that basic requirements of lower lifecycle cost and higher recharge efficiency of WPT over conventional wired or conductive contact recharging can be met, the advantages potentially offered by emerging WPT technologies, include interoperability, ease-of-use, convenience, and environmental sustainability.[8] WPT technologies could also improve system operational safety, since road-embedded infrastructure has no exposed high voltage cables or power outlets for plug-in hybrid and electric buses. Based on the range of WPT demonstrations underway, and/or in-service transit applications discussed in Section 3, their respective Technology Readiness Level (TRL) is evaluated to project their near-term prospects.

Section 4 highlights the Safety, Health, and Environmental (SHE) issues associated with WPT that need to be addressed, as well as applicable U.S. and international regulations and voluntary technical and safety standards. Issues related to the prevention and mitigation of potential SHE impacts for each WPT transit implementation include:

- A critical review of the WPT technology providers for electric transit and respective product performance.
- A survey of the proven capabilities of the diverse wireless charging technologies suited to electric bus and LRV operating requirements and their respective TRL.

- Literature information on the configurations of onboard and EVSE infrastructure, as well as WPT frequency, power, energy efficiency, safety, environmental impacts, and lifecycle cost (to the extent known).
- Identification of existing and in-process applicable technical and safety standards in the U.S. and abroad.
- Projected or proven tradeoffs compared to conventional conductive charging, if known.

Section 5 compares lessons learned to date from WPT transit demonstrations and suggests potential next steps for RDT&E to speed up commercial deployment. Further research is needed in order to improve WPT systems interoperability, reliability, robustness, affordability, and safety and to facilitate commercial deployment in transit fleets. WPT technologies could be widely adopted by U.S. transit fleets, especially if proven less costly than current infrastructure solutions.[9]

SECTION

2

WPT Transit Technology Options and Providers

WPT Principles and Operational Requirements

The principle of IPT (which is a subset of WPT)[10] is depicted schematically in Figure 2-1. IPT occurs when a power supply produces an alternating electric current in the primary coil embedded in the roadway (similar to the primary coil of an electric transformer, as shown on the right), which, in turn, produces a time-changing magnetic field. This variable magnetic field induces an electric current (producing a magnetic field) in the secondary solenoid windings mounted under the bus floor. The induced AC and voltage are then rectified to Direct Current (DC) (in an inverter) to recharge the bus battery. The Rechargeable Energy Storage System (RESS) onboard the bus may also include an ultra-capacitor complementing the battery, since the former can more rapidly charge or discharge. When a transmitter radio frequency (RF) magnetic field matches the receiver frequency, the IPT is called "magnetic resonance."

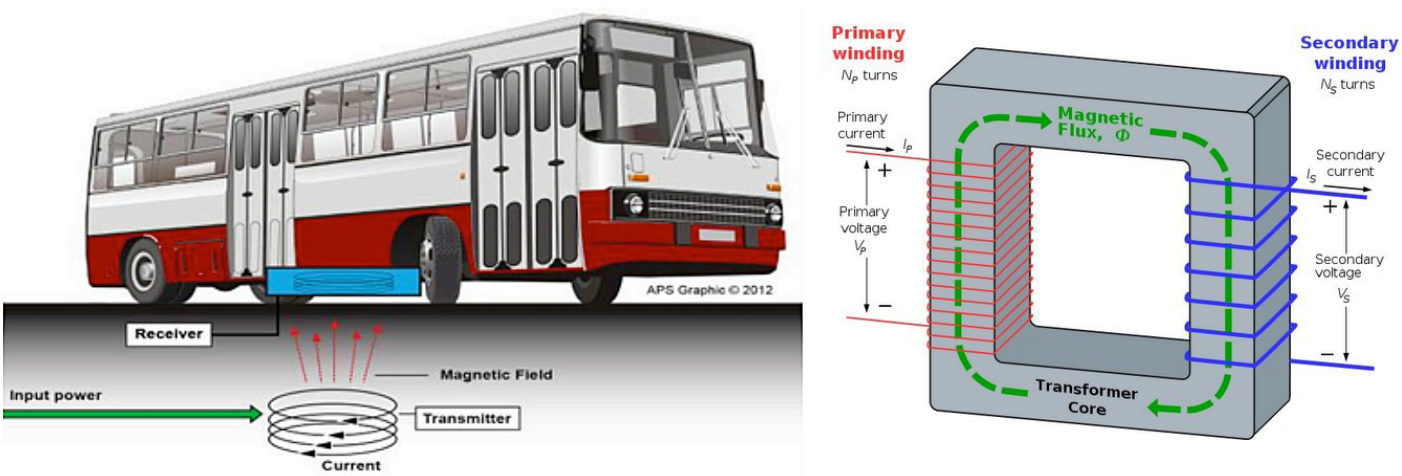


Figure 2-1

IPT/WPT Principle[11]

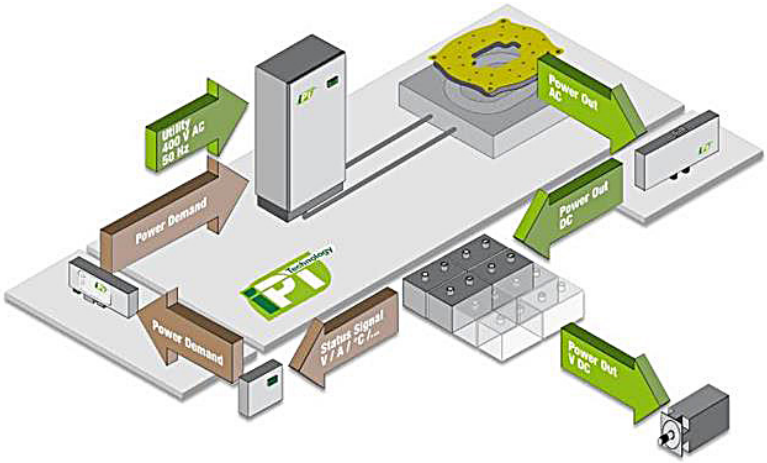
In a transformer, the primary and secondary coils are connected by a magnetic core—usually iron or ferrite—that traps the magnetic flux. For IPT, the magnetic coupling of the primary transmitter infrastructure and the secondary on-board receiver takes place across an air gap using electromagnetic radiation (EMR) for power transfer. Figure 2-1 (left) shows how a magnetic field produced by the primary loop (transmitter) embedded in the pavement induces a current in the

secondary coil (receiver) mounted under the bus. For optimal power transfer at the resonance frequency, the transmitting and receiving coils must be precisely positioned and aligned, with gap size restrictions to limit losses. In addition, a closed circuit is needed to contain the magnetic flux and prevent stray magnetic field emissions. This closed circuit would prevent adverse operational SHE effects. Section 4 discusses the issues associated with the prevention and mitigation of electromagnetic interference (EMI) from IPT charger pads with other vehicle wireless functions, as well as potential RF heating of receiving coils and RF charging of nearby metallic structures.

Emerging WPT technologies for rapid recharging of electric transit bus batteries to extend operational range include both rapid boost charging during brief station stops and dynamic or "on the fly" opportunity charging when the electric bus equipped with receiving coils passes over transmitter coils embedded in the roadway. IPT systems feature a tuned transmitter and receiver. The transmitter consists of primary coils in which electric current produces an alternating magnetic field. The receiver consists of secondary coils in which the magnetic field induces an AC electric current and voltage that can recharge a battery after rectification to DC. The secondary coils are usually placed in close proximity (a few inches) to the primary to ensure efficient power transfer across the air gap and to reduce magnetic field leakage. Several wireless charging technologies and providers of those technologies that involve magnetic resonance are discussed below. The technologies discussed are all currently under active consideration or demonstration for U.S. transit applications.

IPT Technology[12] IPT Charging for Buses[13]

A German IPT Technology company that started in 1996 as Wampfler and then continued as Conductix was spun off in January 2014 as IPT Technology. The company has fielded several generations of electric buses charged by IPT. Their IPT Charge e-Mobility technology provides wireless opportunity charging of hybrid and electric buses equipped with secondary receiver coils. This technology is capable of charging while the bus is stopped or parked over powered (primary inductor) pads embedded in the roadway or in the garage floor.



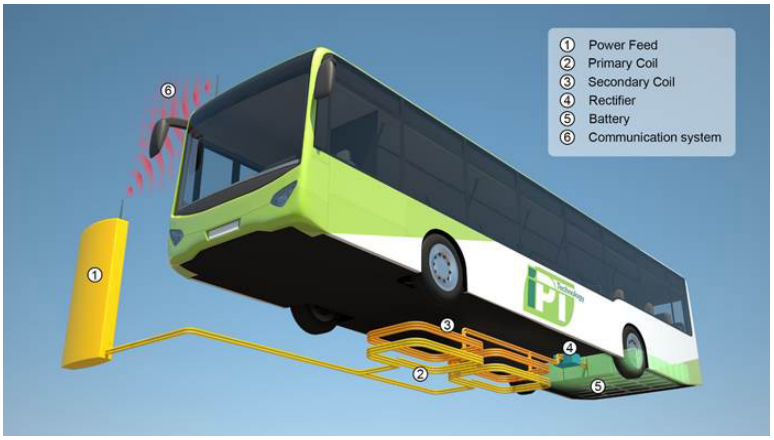


Figure 2-2

Conductix-Wampfler (now IPT Technology) IPT@Charge System[14]

Figure 2-2 shows the schematic of the IPT@ Charge system, which magnetically couples the primary AC-powered coil embedded in the roadway to the secondary pickup coil onboard the bus. These coils operate at a frequency close to 15–20 kHz. The bus battery is inductively recharged across a small air gap of approximately 1.5 inch (less than 4 cm) via a rectifier and voltage control subsystem during station stops. This small air gap is optimal for efficient IPT to minimize spreading and leakage of the magnetic field.[15] The primary coil is powered automatically only when the bus secondary coil is lowered mechanically while above it. Depending on how often the opportunity to recharge occurs, IPT allows for smaller, lighter and lower capacity batteries to be used, thus increasing passenger load. Typically, the IPT energy transfer has exceeded 90 percent efficiency when measured from the grid connection on the infrastructure side to the DC output terminal on the bus battery side.[16] The system is modular for ease of handling and integration and to match the electric bus size. While 60 kW modules are standard for infrastructure transmitters, the bus module size varies with the length of the bus. A 30 kW module is used for buses up to 30 feet long

and a 60 or 120 kW module is used for 40-foot buses. Articulated buses would require a third power module (up to a total of 180 kW).

IPT-Charge technology demonstrations include the first electric vehicles using wireless opportunity charging in the Rotorua Geothermal Park, New Zealand, in 1997/1998 and the first electric buses being charged wirelessly at bus stops and running on an automated basis in Genoa and Turin since 2002. The Genoa and Turin demonstrations continue to operate and are discussed in more detail in a subsequent section. Section 3 reviews the operational deployment of electric buses using this IPT Charge technology in both Europe and the U.S. The latest (2012) IPT system integrates electronic control and communication.

Shaped Magnetic Field in Resonance (SMFIR) Technology[17] for Korean Online Electric Vehicle (OLEV)

The Korean Advanced Institute of Science and Technology (KAIST) research university in Daejon, South Korea, has developed the OLEV green design concept to power electric vehicles wirelessly by SMFIR in 2009. KAIST has filed more than 180 patents on SMFIR and related technologies and described the design and transit bus applications based on SMFIR in several technical papers.[18] A U.S. OLEV Technology, Inc. subsidiary in the Boston, Massachusetts area was established in 2011[19] to commercialize IPT powered electric buses and infrastructure, and was endorsed by both the Massachusetts Clean Energy Center and by MassTransit as a green supplier.[20]

The inductive OLEV charging system shown schematically in Figure 2-3[21] includes:

- A roadside power inverter to bring 60 Hz AC electricity from the grid to road-embedded power tracks at a frequency of 20 kHz (selected for optimal magnetic field coupling and power transfer efficiency)
- Roadway Infrastructure consisting of road-embedded power tracks installed in multiple segments at selected locations of the route; there are 2 power lines with 200 amps of current flowing in opposite directions to form a loop and generate DC power for the electric motor. For efficient power transfer, the only segment turned on is the segment below the vehicle (Figure 2-3, bottom)
- A pick-up coil and regulator kit for the WPT installed in or under the electric vehicle (Figure 2-3, bottom)

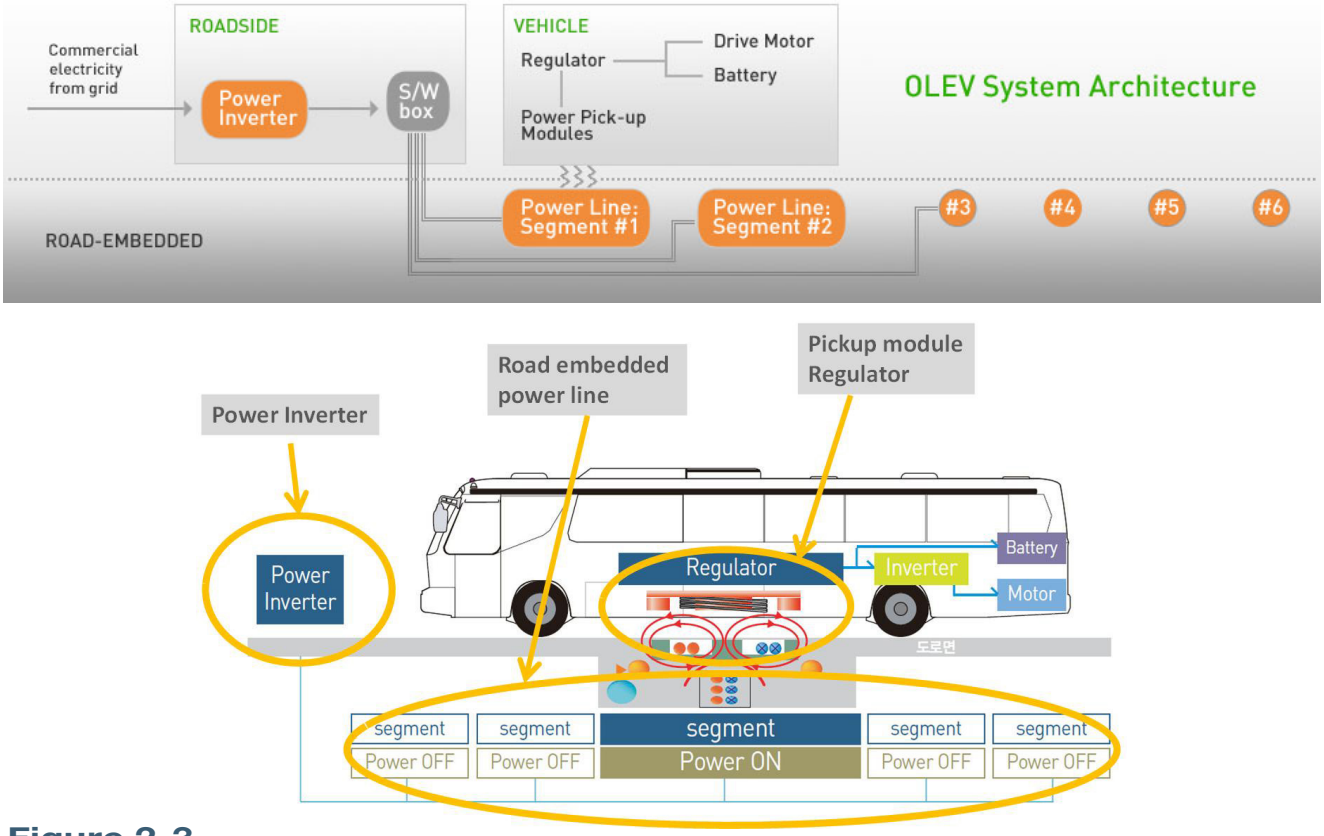


Figure 2-3

Schematics of Infrastructure and Vehicle OLEV SMFIR Bus IPT Subsystems

Figure 2-3 (top) shows a detailed OLEV system schematic of the roadside and road-embedded system segments (to power the primary transmitter), communicating with the vehicle (secondary) pickup coil that feeds current via an inverter (rectifier) to the rechargeable energy storage battery (RESS) and the electric drive motor. The SMFIR chosen frequency for electric buses is 20 kHz, whereas 60 kHz was chosen for rail WPT.[22] Figure 2-3 (bottom) shows a more complex view of the OLEV SMFIR system architecture. This bottom schematic shows the onboard receiver coils with optimal inductance matching for efficient WPT power transfer. The 60 kW of power is transferred from power lines to the bus pickup module that then recharges the Kokam lithium ion phosphate bus battery. The dynamically charged OLEV bus battery capacity is designed to be only 20 percent of a conventional electric bus to reduce both battery weight and cost.

The OLEV road-embedded power tracks are deployed in segments of variable lengths from 1 meter to 1 km along 15 percent or more of the bus route, depending on the duty cycle required to recharge the battery. OLEV buses and infrastructure are operating both at the KAIST Daejong campus test site and in

Gumi, South Korea (see Section 3). The electric buses operating in South Korea receive up to 100 kW power at 85 percent transmission efficiency across a 20 cm fixed air gap between the road surface and the bus underbody.

OLEV uses both active and passive magnetic shielding to address the SHE issues discussed below in Section 4. Shielding provides a number of benefits including directing magnetic fields between primary and secondary coils, reducing EMF emissions, and reducing exposure levels to passengers in the vehicle and in stations all while ensuring efficient WPT.[23]

Wireless Advanced Vehicle Electrification (WAVE)

Utah State University (USU) spun off the WAVE startup[24] to commercialize IPT technology for electric buses after developing it within its Electrodynamics Lab.[25] A primary transmitter of 50kW power at 20kHz is embedded in the roadway, and an identical secondary receiver is mounted underneath the bus, allowing wireless power transfer over a large air gap of 6-10 inches. The initial WAVE technology bus demonstration prototype was a campus shuttle (Aggie Bus), which modified a 22-foot electric eBus to recharge its nickel cadmium battery (NiCd) for 5 minutes every 15 minutes. The Aggie Bus has achieved 90 percent power transfer efficiency for 25 kW at 20 kHz across several inch air gaps during station stops over road-embedded powered coil generating the IPT magnetic field.[26]

Noted improvements in IPT include the use of ferrite cores to trap and focus magnetic fields produced, use of woven Litz wire windings on transmitter and receiver coils to reduce electrical losses, along with advanced power electronics for conversion and control. Other planned improvements[27] include higher power, frequencies (up to 140 kHz), mobile IPT (besides the current station recharging), and increased misalignment tolerance from 8 inches at a 6-inch fixed air gap, to 10 inches at a 15-inch air gap.

With FTA TIGGER-3 funding, USU and the Utah Transit Authority (UTA) will recharge the lithium iron phosphate batteries of a 40-foot bus during stops up to 50 kW power. The bus has been delivered and the charging pads installed. The bus has demonstrated inductive charging capability, and UTA will do further testing before placing the bus into service over a 1.5 mile route. Operations are scheduled for revenue service in April 2014. Besides the opportunity IPT charging at the station, WAVE buses will also be conductively recharged overnight in the garage. Therefore, its battery management system (BMS) is programmed to accept both DC conductive and pulsed WPT power. More details on the planned WAVE projects for Long Beach Transit [LBT], Monterey Transit System [MST], and McAllen, TX are presented in section 3.

Bombardier PRIMOVE IPT for Electric Buses[28]

As discussed in Section 3, Bombardier has developed a full suite of e-mobility solutions for electric transit using proprietary IPT technology, including a high power (200 kW) rapid IPT opportunity charging system for electric buses. This system requires a smaller and lighter onboard PRIMOVE battery, claimed to have extended life and reduced energy consumption, while enabling larger passenger loading. Demonstration and implementation of the PRIMOVE IPT for electric buses is underway in Mannheim and Berlin, Germany, and in Bruges, Belgium.[29] The compact and lightweight water cooled lithium ion battery packs (50–90 kWh) are supplied by the German AKASOL manufacturer.[30]

The schematic in Figure 2-4 shows the PRIMOVE IPT components onboard the electric bus, including the power receiver pickup coils and a compensation condenser to convert the magnetic field from the primary into an AC, inverters (rectifier) to convert AC to DC for the battery, the RESS or battery, and a Vehicle Detection and PRIMOVE segment control (VDSC) antenna to detect the primary cables and control the on-off switch.

Figure 2-4

PRIMOVE Bus Wireless Charging Diagram [31]

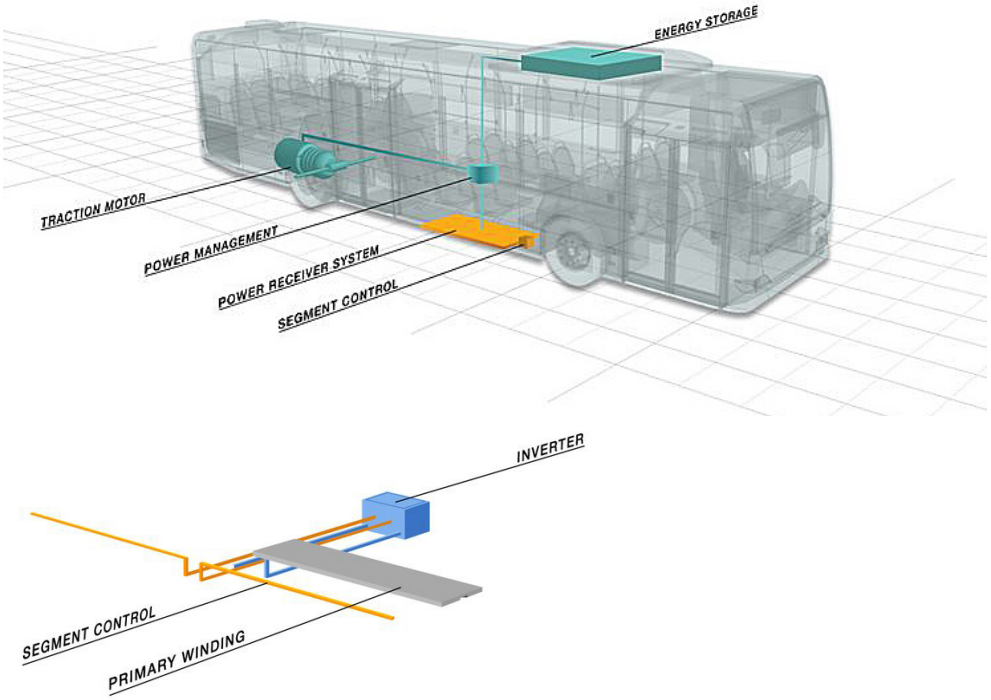


Figure 3-7 is a PRIMOVE IPT system schematic used to power both electric buses and light rail trams while stopped over the transmitter embedded in the pavement. These components include primary cabling for power transfer, magnetic shielding under the primary winding to prevent EMI to and from nearby sources: a Vehicle Detection Segment Control (VDSC) cable that senses the bus above it and turns on the power; a Supervisory ,Control and Data Acquisition (SCADA) to provide information for system control and failure diagnostics, inverters that convert the DC LRV supply voltage to the AC at IPT frequency used by the system, and DC feed cables to supply power to the inverters.

The German partnership between Viseon Bus, Gesellschaft mit beschränkter Haftung(GmbH) and PRIMOVE has developed a mechanical lifting and lowering mechanism for extending the pickup coils onboard for most efficient recharging.[32] It is located under the bus floor and extended downwards to reach the maximum magnetic field when above the primary loops embedded in the pavement. For static re-charging at bus stops, the power pickup coil can also be positioned on the floor for maximum power transfer rates. Rollers on the pickup coil maintain sufficient distance to the power pickup to prevent damage. This patent-pending lifting and lowering mechanism was designed to also allow recharging while the vehicle is moving.

Other WPT Technology Providers

Several other WPT technologies for small electric vehicles (EV) have been developed and demonstrated and are being evaluated prior to commercialization. The majority of these other WPT technologies are of the IPT variety. Although not yet applied at the high power transfer levels required for transit bus implementations, they are an important technology test-bed to resolve potential safety and efficiency issues, and to standardize and commercialize IPT infrastructure and vehicle subsystems and components.

Qualcomm HaloIPT[33]

In 2011, Qualcomm acquired HaloIPT, a New Zealand company (spun off by the University of Auckland) that developed wireless induction charging technology in the late 1980s for electric vehicles. In 2010, HaloIPT successfully charged the Citroen EV and partnered with Rolls Royce to charge its luxury Phantom EV. Currently, 100 EVs equipped for HaloIPT charging are being evaluated in London.[34] HaloIPT research showed that the Low Frequency (LF) bands widely used for wireless electric vehicle charging applications must be optimized for HaloIPT EV charging power transfer at 3.3–20 kW.[35] Electric buses would need much higher power transfer (60–120 kW boost to full charge output power.)

WiTricity[36]

In 2007, a Massachusetts Institute of Technology (MIT) faculty and researcher team demonstrated and patented a WPT technology[37] that uses magnetic resonance (as opposed to induction) for power transfer over larger gaps. This Highly Resonant (HR) WPT has achieved efficiency of over 90 percent via strong magnetic field coupling of resonator coils at longer distances (15 cm to 2 meters) for a broad range of potential applications.[38] This technology was since been optimized for higher tolerance to misalignment and greater gaps (for a mid-range of 2 meters) between the receiver and transmitter coils. Measurements of an RF magnetic field were performed to demonstrate compliance with limits recommended by international human exposure safety standards, further discussed in Section 4.[39] Efficient HR-WPT recharging of batteries in small electric vehicles—but not yet buses—was demonstrated in 2011,[40] leading to licensing partnerships with major automotive manufacturers (Toyota, Audi, Mitsubishi Motors, and Delphi).[41]

EVATRAN PluglessPower[42]

EVATRAN has developed Plugless Power, a Level 2 (3.3 kW) inductive charging EVSE for stationary rapid charging and is commercializing it in partnership with Bosch. It consists of a vehicle adapter customized to each EV model placed under the vehicle and a control panel linked to a 240 V, 30 amp electrical power supply that provides power to the parking pad on the floor of the garage, guides the driver to park over the pad, and displays the battery State of Charge. The system technical specifications[43] and safe operability were tested by the Department of Energy (DOE) Idaho Engineering Lab,[44] which confirmed that it complies with EMF human exposure safety limits. To date, more than 1,500 hours of Plugless Power testing were successfully completed[45] with leading fleets of electric Chevy VOLT and Nissan Leaf.

Eaton HEVO and Momentum Dynamics

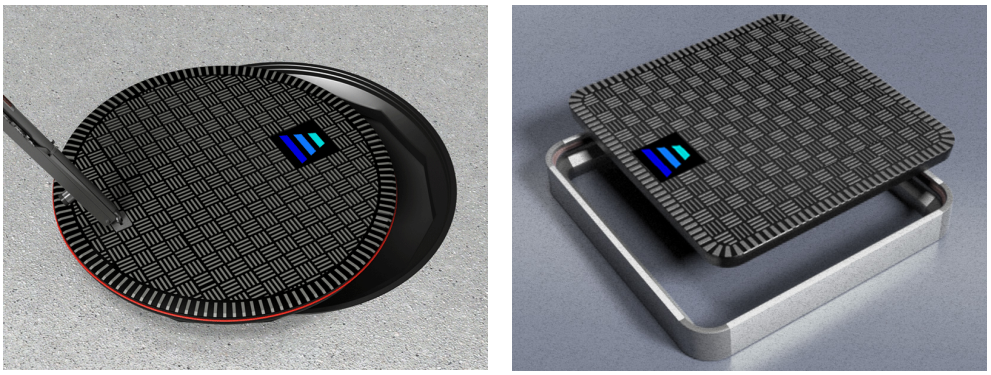
In December 2013, Eaton Corporation announced the commercial availability of a scalable (200 kW to 1 MW) HyperCharger[46] for fast charging hybrid and electric buses and trucks. Press articles claim it has already been installed in Tallahassee, Florida, Worcester, Massachusetts and Stockton, California, for use with Proterra's EcoRide BE35 bus. It appears that 8 en-route charges have extended the electric bus range to 240 mi per day.[47]

HEVO Power[48] is another IPT contender for urban dynamic IPT charging infrastructure. For instance, HEVO[49] was developed (and is being tested) in New York City manhole covers (round or square, as shown in Figure 2-5) that integrate primary induction coils and antennae. These IPT manhole covers activate to transfer power when EVs equipped with intelligent transceivers drive over them at normal road speeds.[47]

Momentum Dynamics Corporation[50] of Malvern, Pennsylvania, has also developed a high-powered WPT product that supports dynamic charging of larger electric and hybrid-electric commercial fleet vehicles, including buses. Current field trials are in progress, with systems that could transmit 30 kW of power across a 12-inch air gap in rain or snow.[51]

Figure 2-5

EV Power Systems[52]



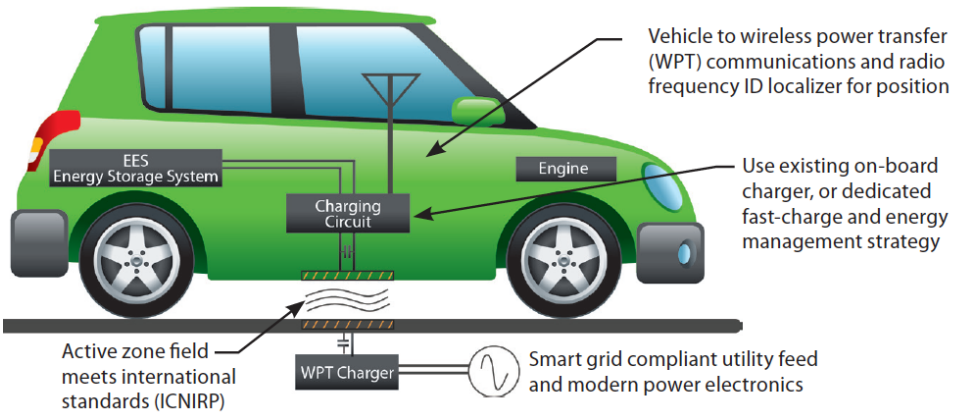
Other WPT technology providers teamed up with electric vehicle manufacturers, such as Fulton Innovations (with its eCoupled[53] charger for Tesla Roadster) and Powermat[54] offering WPT for the GM for the Chevy VOLT. As these technologies mature, scale-up of IPT power and perhaps frequency optimization from small EVs to large transit buses may be needed.

DOE National Labs Development of WPT Technologies and Support of Interoperability Standards

The DOE Oak Ridge National Lab (ORNL) has developed, improved, evaluated, patented, and is currently licensing a WPT system and associated technologies for stationary (garage) or dynamic (roadway) recharging of electric vehicle batteries.[55] The ORNL WPT system provides sufficient power for even imprecise alignment of magnetically coupled coils (see Figure 2-6). ORNL's recent conference presentations describe its WPT technology improvements, demonstration, test, and evaluation on Prius and VOLT Plug-In Hybrid Electric Vehicles (PHEVs), frequency optimization and power transfer efficiency, and the verification of safe operability and compliance with human exposure safety standards to radio frequency radiation (RFR) and magnetic fields.[56]

Figure 2-6

ORNL Static or Dynamic WPT System



For instance, conventional IPT charging systems maximize power transfer by increasing the power load near the resonance frequency. However, ORNL found that there is a loss of efficiency when operating near the resonance point. ORNL's technique found that sufficient power for the battery can be transferred from the primary to secondary circuits without significant energy losses even if the operating frequency is set at 50–95 percent of the circuit resonance frequency. The battery, which is electrically coupled to the secondary circuit through the air core transformer, is recharged.

SECTION

3

Demonstration and Deployment of WPT Electric Bus and Light Rail Systems

Electric Bus WPT Demonstrations

WPT US Projects

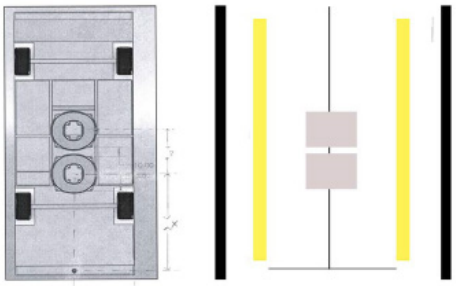
To facilitate and speed up the adoption of electric buses using advanced WPT technologies, the FTA TIGGER program[57] and the Clean Fuels Grant program have awarded several electric bus projects using different WPT technologies to rapidly recharge electric bus batteries in a mobile setting or in stations. These demonstration projects are in early planning, deployment, and evaluation stages, so it may be too early to determine their long-term commercial viability.

Recent, ongoing, and planned U.S. WPT bus demonstrations are described below:

- The Chattanooga Area Regional Transportation Authority (CARTA), in partnership with the Center for Energy, Transportation and the Environment (CETE) at the University of Tennessee, Chattanooga (UTC), has demonstrated the effective boost recharging of three 30-foot electric buses using the IPT Technology (formerly Conductix-Wampfler) IPT.[58] It should be noted that CARTA no longer is working with CETE on developing specifications.
- Figure 3-1 shows the CARTA Electric Shuttle Bus (left). It was modified by the CETE/UTC team with the IPT Charge (Conductix) technology for range extension. The on-board receiver coils (right) received fast opportunity boost charging (60 kW at 20 kHz for 3 minutes) while in station stops when aligned with IPT transmitter coils embedded in the roadway. The original on-board Nickel-Cadmium battery capacity was increased to the point that bus range more than doubled from the previous all electric range of 44 miles. This increased capacity and range requires a full, slow, overnight recharge in a parking garage, for example.

Figure 3-1

CARTA Electric Shuttle Bus



- The University of Utah (UU) campus in Salt Lake City and the Utah Transit Authority have collaborated on demonstrating IPT for the Aggie campus electric shuttle bus, using the UU-developed WAVE[59] IPT technology. The WAVE technology is also being adopted for charging the Long Beach, California, electric buses[60] as well as by the Monterrey-Salinas Transit (MST) trolleys in California.
- The FTA TIGGER program funded Long Beach Transit (LBT) to purchase 10 electric buses to enable its wireless recharging. However, recent integration challenges, implementation delays, and meeting Buy America requirements have resulted in some open questions about this particular project.[61,62]
- The Maryland DOT, the Center for Transportation and Environment (CTE),[63] and Howard County, Maryland, will operate three inductively-charged electric buses on the Baltimore Green Route in Columbia, Maryland. This project is in the early stages of implementation, with a second RFP having been issued in December 2013 after the first June 2013 RFP was considered non-responsive.
- McAllen, Texas,[64] was funded in 2011 to equip three electric buses with the OLEV Shaped Magnetic Field Resonance (SMFIR) technology developed by KAIST. However, delays and problems in contract award to OLEV and later to EV America led to a late award to WAVE in October 2013.[65]
- In 2012, FTA's Clean Fuels Grant program also included two electric bus awards[66] using WPT. These projects include the MST trolley project, which plans to use WAVE induction technology,[67] and the Nashville Metropolitan Authority[68] purchase of electric buses and IPT station infrastructure (from an as yet undefined provider).

International WPT Bus Demonstrations and Deployment

Demonstrations and deployment of in-service operations of wirelessly recharged buses have been underway in Europe and Asia for the past decade.[69] The examples below provide operating experience relevant to similar U.S. transit applications.

Italy

The IPT Technology (formerly Conductix-Wampfler) for charging electric buses in the station could be considered mature. It has been successfully deployed to power more than 40 electric buses that have operated in Turin and Genoa for more than a decade.[70] In Turin, a fleet of 23 electric buses received boost charge batteries while stopped in station to drop and board passengers. The Conductix-Wampfler IPT® Charge system was rated at 60 kW and operated at 90 percent power transfer efficiency. The reported annual cost of electricity per bus was about $9K, a substantial gain compared to $50K fuel cost for a diesel-powered bus.

Germany

Two electric buses are being tested for 12 months in Mannheim. The pad is activated only when the bus is above it.[71] Initially, the 12-meter Solo ebus will be recharged during a 10-minute stop at terminus. When longer 18-meter articulated Solaris buses are introduced, two more embedded IPT pads at intermediate bus stops are planned for opportunity recharging. Electric ebuses using the PRIMOVE IPT are recharged at more than 200 kW pads in public areas. These particular buses are currently operating in Mannheim. A similar Solaris Urbino electric bus equipped with Bombardier PRIMOVE wireless charging while stopped in stations (Figure 3-2) started operations in Braunschweig, Germany, in December 2013. Current plans are to also equip buses in Bruges, Belgium, with this PRIMOVE IPT.

Figure 3-2

12m Solaris Urbino Electric Bus in a PRIMOVE-Equipped Electric Bus [72]

Photo ©Bombardier

Netherlands

In s'Hertogenbosch, Netherlands, a Volvo 86-passenger bus (see Figure 3-3) has recharged its lithium iron phosphate batteries using Conductix-Wampfler IPT since 2012 by using 120 kW of charging modules (2 modules of 60 kW EA) during station stops.[73] It is equipped with a mechanism to automatically lower the on-board pickup coils to be close to the primary coil in the asphalt during battery recharge opportunities for optimal IPT efficiency. Another bus is operating in Utrecht.

Figure 3-3

Bus Using IPT Technology Inductive Charging While in Station[74]

Switzerland

Asea Brown Bovery (ABB) Ltd. is testing an articulated electric bus serving the city-to-airport shuttle in Geneva using the new flash charging concept named Trolleybus Optimisation Système Alimentation (TOSA). It can provide charges in 15-second bursts of 400 kW at selected stops along its route, using a charging station that connects to the top of the vehicle.[75] A full battery charge takes 3–4 minutes at the final stop.[76] Such rapid recharging is very demanding even for lithium ion bus batteries, both for WPT and in accepting regenerated braking power. The BMS must aggressively manage the power input (charge) rate to the battery as well as the delivery (discharge) rate, so as to prevent potential damage to the batteries due to overcharge, overheating, and potential fire hazards.

Electrical energy received by both roof-mounted charging equipment and regenerated braking energy stored in compact and smaller batteries. As with most other ebus systems, these batteries power the bus traction system as well as auxiliaries (interior lighting and cooling). However, in this case, the roof-mounted charging equipment does not appear to be an IPT mechanism, since conductive charging of the battery takes place when a robotic arm on the bus makes contact with the overhead charger in station stops. The TOSA electric bus recharge (see Figure 3-4) is referred to as "wireless" nonetheless because of the absence of the usual overhead, continuous trolley wires.

Figure 3-4

ABB TOSA Flash-charging System

United Kingdom (UK)

In January 2014, a fleet of eight Wright-bus electric buses was launched in Milton Keynes near London. This bus fleet is using IPT Technology to extend its range after overnight depot recharging of batteries.[77] It will operate on a demanding schedule and route (17 hrs/day on a 25 km route for 56,000 mi per year), and the boost is charged wirelessly at line ends. In 10 minutes, while parked over the IPT charge pad at either end of the line, the bus will recover 2/3 of the energy consumed over the 15-mile route. The bus fleet performance, reliability, and cost will be evaluated over five years to assess commercial viability. This IPT Technology is similar to the electric buses operating in Turin, Genoa, Utrecht, and Mannheim.

South Korea

Two KAIST/OLEV wirelessly-recharged electric buses have been deployed and are being evaluated in South Korea.[78] The bus shown in Figure 3-5 is one of the two operating in 2013 on a 24 km (15 mi) line in the city of Gumi, South Korea. The advantage to the KAIST/OLEV system is that the rechargeable bus battery is smaller than usual, at only 1/5 the size of a normal electric bus battery. Recharging pads cover only 10–15 percent of the bus route.[79]

Figure 3-5

KAIST OLEV Electric Battery Bus[80]

Japan

Hino Bus, a division of Toyota, developed and tested a fleet of hybrid electric buses with lithium ion batteries and receptor coils under-carriage recharged by pavement embedded induction coils in 2008. The buses operated on a 4.2 km route at Haneda Airport in Tokyo. No technology details on the WPT frequency, gap separation between bus and road embedded coils, power efficiency and duration were found in 2008 references,[81] and it is unclear if these buses are still in operation.

Another advanced electric microbus—the Waseda Electric Microbus-3 (WEB-3)—was inductively recharged from overhead. The WEB was developed and tested in operation in Nagano City, Japan, by Waseda University researchers.[82] An improved inductive power supply was embedded in the roadway, recharging the WEB-4 mini-bus batteries with 92 percent efficiency across an air gap of 1.40 cm. The improved WPT-powered bus was operationally demonstrated on public roads in Honjo and Kumagaya, Japan.

China's BYD Electric Buses

More than 200 BYD electric buses (K9 in China) have been operating in Shenzhen, Changsha, and other Chinese cities since 2010. The eBus is powered with its BYD-developed lithium iron phosphate batteries featuring a driving range of up to 250 km (155 miles) on a single charge. The maximum range requires six hours for a full recharge overnight or three hours for a fast charge. The Los Angeles County Metropolitan Transportation Authority ordered 25 49-foot BYD plug-in electric buses in 2013, with an option for 20 additional buses. BYD supplied a K9 bus to be retrofitted with WAVE's wireless charging pad under the bus in 2012.

WPT for LRVs

Adoption of WPT technology for electrified monorail, LRVs, trolleys, and electric streetcars could enable the revitalization of their operations in congested city cores without the use of existing unsightly pantographs on vehicle roofs and overhead contact or catenary system (OCS) wiring. Proposed WPT for LRVs and trolleybus operations in city centers promises to replace the conventional OCS and wayside traction power supply substations and vehicle roof pantographs with more aesthetic in-ground power infrastructure. This new infrastructure will also have improved safety due to no exposed high voltage cables and be a less costly investment in OCS and support poles. The benefits of contactless power transfer for urban rail transit claimed by providers[83] include reduced visual pollution in historic city cores, reduced infrastructure and maintenance, all-weather operability, reduced vandalism and safety risks, and a claimed reduction of energy consumption by up to 30 percent when combined with onboard energy storage. Transit systems to be powered inductively are planned for Sydney, Australia, and

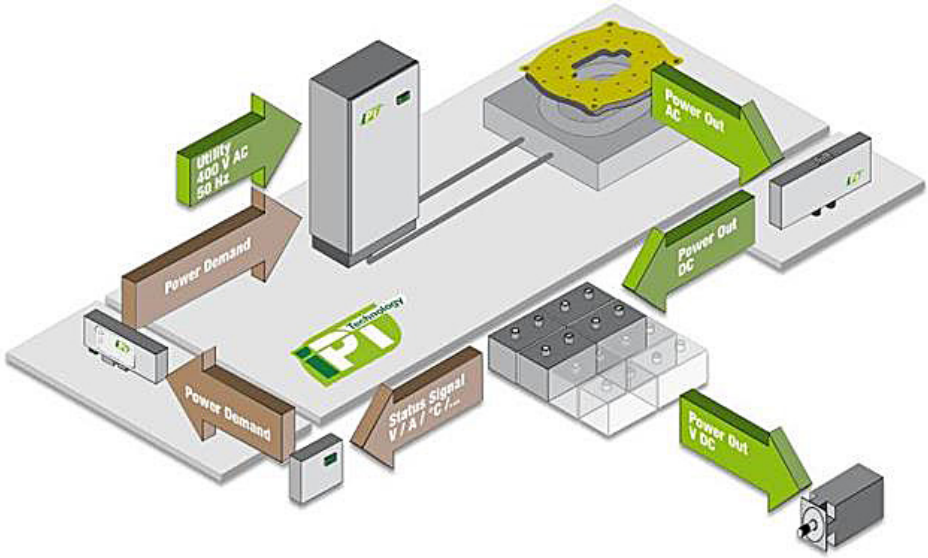
for Nanjing, China.[84] Available WPT technology options for light rail are briefly reviewed below.[85,86]

IPT-Rail from IPT Technology (formerly Conductix)[87]

The current IPT Technology Gmbh (formerly Conductix) Rail architecture shown in Fig 3-6 can deliver between 320 and 4,500 amps to power automated people movers (APMs), personal rapid transit, light rail transit, and monorail systems. Controllers and a proprietary Power Rail Impact Analysis System diagnostic tool are designed to improve rail system performance by measuring and locating hot spots and inconsistencies in the rails and to ensure efficient contactless power transfer from powered segments to vehicles.

Figure 3-6

IPT Technology Gmbh (formerly Conductix) Installation Schematic[88]



Bombardier PRIMOVE Wireless Powering FLEXITY Freedom Trams

The Bombardier PRIMOVE IPT for urban rail vehicles is part of its ECO4 IPT solutions for transit exhibited at the APTA EXPO 2011 in New Orleans, U.S. These IPT solutions "are built on the four cornerstones of energy, efficiency, economy, and ecology."[89] IPT rail was developed to eliminate the overhead catenary system (OCS) power supplies wiring and pantographs. They are replaced with a contactless infrastructure system installed beneath the track coupled to on-board components.

The electric current in the primary winding wayside component of the system is shown in Figure 3-7. It creates a magnetic field, which induces the electric current in the coil onboard the vehicle. The on-board components include a pickup coil system and a compensation condenser (the PRIMOVE Power Receiver System) underneath the LRV, which converts the primary winding magnetic field

into alternating current, further rectified into DC using an inverter. The cable-powered primary segments are detected by the Vehicle Detection and PRIMOVE Segment Control (VDSC) antenna in the vehicle and switched on. The PRIMOVE system can provide a power output ranging from 100 kW to 500 kW, depending on LRV-specific needs (length, the number of cars, geographic conditions and range). It can be used for LRVs with length varying from 30 to 42 m, a gradient up to six percent, and speeds up to 50 mph running on 270 kW power.

The PRIMOVE Light Rail Tram IPT was introduced in 2009 and first installed for demonstration, test and evaluation on a 0.8km branch of the Augsburg, Germany line serving the exhibition center since May 2010. Tests on this 200 kHz induction loop spur line were completed in June 2012. There are planned IPT wireless power options for several Movia metrocars and Flexity Freedom LRV rail train-sets, though it's unclear if they are already operating in inner cities in Germany.[90] The PRIMOVE "contactless" EcoActive track and urban LRVs (Figure 3-8) was also exhibited at APTA in 2011, seeking U.S. commercial deployment opportunities.[91]

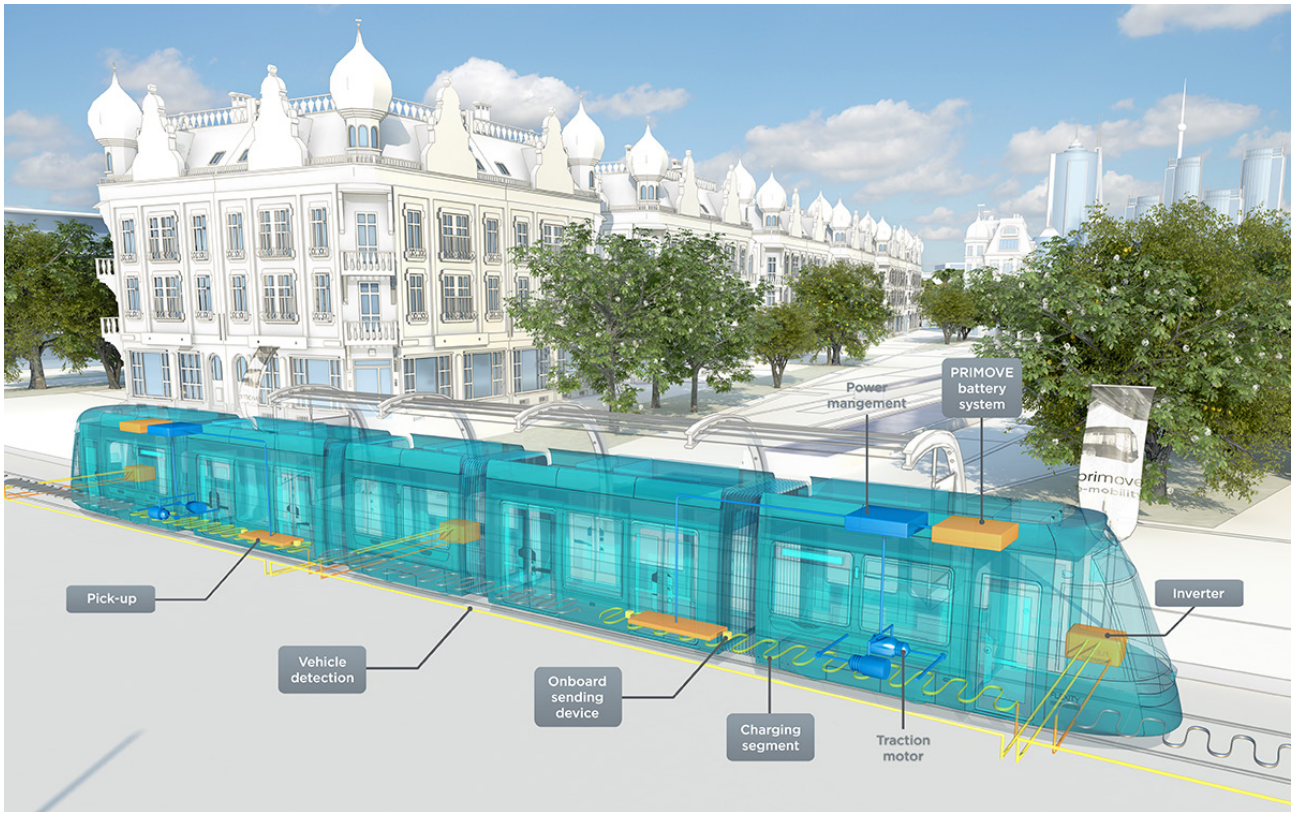


Image ©Bombardier

Figure 3-7

PRIMOVE Schematic[92]

Figure 3-8

PRIMOVE EcoActive Light Rail

Image ©Bombardier

Alstom APS Underground Power for LRVs

The Alstom Transport Alimentation Par Sol, or Aesthetic Power Supply (APS) in-ground wireless power system for inner city LRV transit system,[93] has replaced catenary and pantographs with a set of powered loops embedded in the pavement. On board the LRVs is an antenna and contact shoes so that the in-ground loop segment is activated only when the LRV is above it.

Though not strictly an IPT technology, APS power transfer enables the tram to travel "wirelessly," since the LRV power is supplied via a third rail embedded in the roadway track. The energy is captured by two collector slippers located under the tram center. For pedestrian safety, charging of the LRV in-ground buried conductor segments is triggered only when they are covered by the tram.[94]

Figure 3-9

Bordeaux INNORAIL[95]

The APS advantage in historic inner city tracks is that overhead electric lines are replaced by a ground level third rail that provides power via contact shoes from in-ground power to trams equipped with an antenna and switch to activate the power supply while above a track segment. Currently, five cities in France have operational Citadis light rail transit systems powered wirelessly by the APS in-ground supplies. Tours is the fifth city in France to introduce the APS wireless

technology for its Citadis tramway, after the first Bordeaux system (operating since 2000, shown in Figure 3-9). Deployments in Angers, Reims, and Orléans (in 2006) followed.

Siemens Mobility Sitras Hybrid Energy Storage (HES) System[96]

As part of its Mobility solutions[97] for sustainable LRV operations, Siemens has developed and deployed since 2009 the Sitras HES and the Sitras Mobile Energy Storage (MES) products. They integrate reliable NiMH traction batteries and double layer capacitors (or ultracapacitors) on LRV roofs. HES can capture, store and deliver regenerative braking energy, providing a 1.5-mile range in city centers without OCS wiring.

The KAIST OLEV for High Capacity Rail

In February 2013, KAIST and the Korea Railroad Research Institute (KRRI) announced[98] that the SMFIR OLEV technology was successfully tested and demonstrated to transfer 180 kW of power at 60 KHz to rail vehicles on a track at Osong Station in Daejong, South Korea. KAIST and KRRI planned WPT tests for both electric trams and high speed rail in 2013. Improvements were reported in power transmission density by a factor of 3, as well as reduced size and weight of the pickup modules onboard the vehicle, as well as lowering production costs for major OLEV system components.

SECTION

4

SHE Standards and Regulations Relevant to IPT

Electromagnetic Spectrum and IPT Frequency Bands

The use of the electromagnetic spectrum (Figure 4-1) is regulated by the Federal Communications Commission (FCC)[99] and frequency bands are carefully allocated to enable and protect both public and commercial uses. Shared use of spectrum bands may be permitted with safeguards protecting operational safety and security (e.g., coding and encryption) that prevent EMI due to frequency encroachment and, from increasing demand for wireless and mobile services. FCC approval is needed for the use of frequency bands, including Industrial, Scientific, Medical (ISM), and Intelligent Transportation Systems (ITS) applications. It is necessary to prevent EMI with allocated radio services, automotive electronics (i.e., keyless entry, tire pressure, ultrasonic garage remote) and non-automotive systems (RFID, security devices).[100] FCC regulations assure the operational safety of new transmitters or susceptible devices by protecting licensed or allocated frequency bands[101] from EMI due to encroachment from emerging new users.[102] FCC regulations also require and enforce RFR limits from licensed transmitters[103] that ensure environmental and human exposure safety from EMF and EMR.

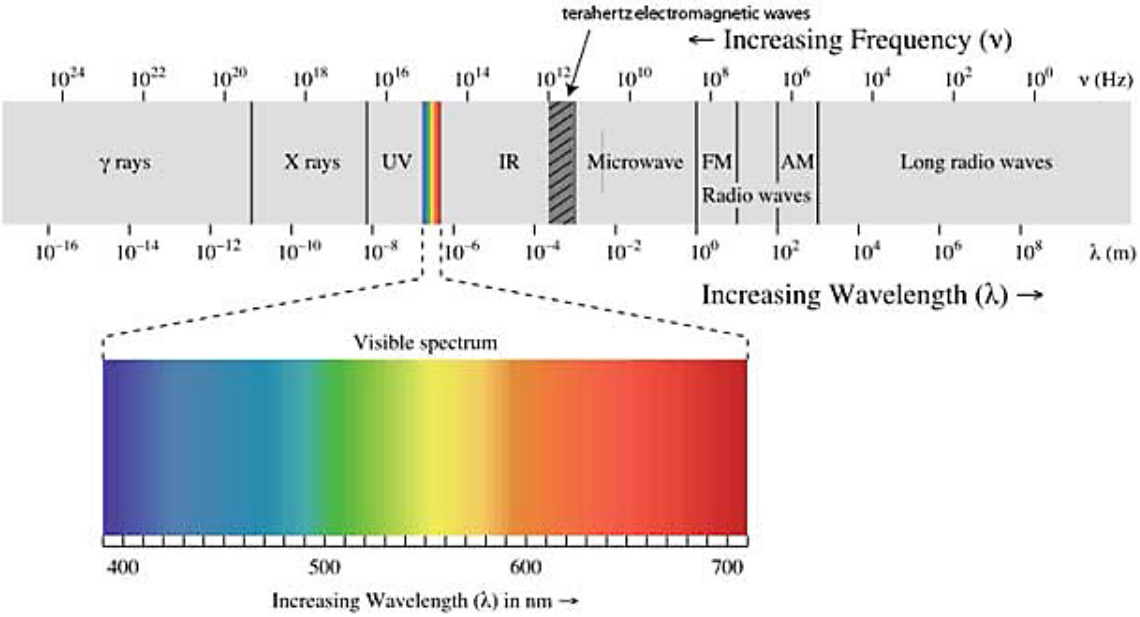


Figure 4-1

Electromagnetic (EM) Spectrum

The lower the frequency of EM radiation, the longer the wavelength and the size of the antenna required to transmit and received EM energy. The Very Low Frequency band ranges from 3–30 kHz and corresponding wavelengths from 100–10 km. The LF band extends from 30–300 kHz. Below 100 kHz in the LF band, the electric and magnetic fields can essentially be decoupled and treated quasi-statically. At 1 MHz, the wavelength is 0.3 km, at 100 kHz, it is 3 km, but at 20 kHz used by several IPT providers, it is 15 km. In IPT systems, the transmitter and receiver are closely spaced, or "near-field," (within a quarter wavelength, or tuned in resonance for optimal magnetic fields coupling efficiency).

International Technical Standards

In 2013, the International Standards Organization (ISO), in cooperation with the International Electrotechnical Commission (IEC), issued the standard ISO 15118[104] for EV to grid communication. It specifies the communication protocol between EVs, including battery electric vehicles, PHEV, and EVSE. The communication standards between the Electric Vehicle Communication Controller and the Supply Equipment Communication Controller, components are also defined. ISO has also issued the standard ISO 14117 for active implantable medical devices in 2012. This ISO 14117 standard specifies test methodologies for the evaluation of the electromagnetic compatibility of active implantable cardiovascular devices that provide one or more therapies for bradycardia, tachycardia and cardiac resynchronization. It specifies performance limits of these devices, which are subject to interactions with EM emitters, such as the various WPT systems, across the EM spectrum.

IEC Technical Committee (TC) 69 is developing a set of WPT technical standards for electric vehicles, including:[105]

- 61980-1, Electric vehicle WPT systems Part 1–General requirements
- 61980-2, Part 2–Specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to WPT systems
- 61980-3, Part 3–Specific requirements for the magnetic field power transfer systems

U.S. Technical and Safety Standards for WPT

Several U.S. Standards Developing Organizations accredited by the American National Standards Institute (ANSI) have also developed relevant WPT and EVSE standards specific to the U.S. transit and vehicular operating environment. SAE is developing interoperability standards for both contact conductive or wired chargers, and for wireless charging of EVs and PHEVs. SAE J2953/1 and J2953/2[106] are SAE Recommended Practices for technology-neutral conductive wired charging, specifying EVSE to EV interoperability and test procedures.

Standards J2836/6 (use cases for wireless communications for PHEVs) and J2847/6 (wireless charging communications between PHEV and the utility grid) address

WPT communication protocols. A similar effort is underway by the SAE J2954 Wireless Charging Task Force (TF)[107] to develop voluntary industry standards for wireless charging frequencies, positioning, power transfer efficiency and speed by levels. This TF has a working group on bus WPT standardization (see Table 4-1), requiring high IPT levels (WPT3) of 150 kW at 90 percent efficiency for electric buses. Both ORNL and the Argonne National Lab[108] are supporting the TF in the development of WPT standard J2954 to ensure both IPT chargers interoperability and optimal power transfer and companion IEEE Standards Association (SA) development of standards for PHEV/EV communication with charging infrastructure and the smart grid.

In November 2013, the SAE J2954 TF announced[109] that an agreement was reached on WPT common frequency of operation that would ensure interoperability. The WPT LF band centers at 85 kHz, but ranges from 81.38–90 kHz. This frequency band is available in both the U.S. and internationally. The LF electromagnetic (EM) RF spectrum extends from 30–300 kHz, which correspond to long wavelengths (10 km to 1 km). Effective power transfer between transmitter and receiver via magnetic field coupling is usually achieved within a quarter wavelength separation, at "near-field" distances.

The Idaho National Laboratory (INL)[110] developed WPT test protocols and published technical and safety performance findings for WPT equipment.[111] Human exposure levels to magnetic fields as a function of distance were measured for safety certification of the EVATRAN Plugless Power to facilitate deployment.

Table 4-1

SAE Task Force for J2954 Wireless Charging Standard[112]

Classification (example for discussion)			Power Class		
			WPT1 L.D. Home	*WPT2 L.D. Fast Charge*	*WPT3 Bus*
A	**EVSE: Transmitter**	**Maximum ESVE Power Source**	**3.6 kW**	**19.2 kW**	**150 kW**
		Min. efficiency at rated power (Grid to battery input>SAE J2954/SAE Standard Test with defined Equipment and Ground Clearance category)	90%	90%	90%
B		Coil/field specification (see study)	TBD (Options 1-4)		
C		Frequency	**One frequency for interoperability**		
		Communications/alignment	DSRC/RFID		
D		Coil location in parking space (more for buses)	Center axis of vehicle/Y Direction TBD		
E	**Vehicle: Receiver**	Coil location on vehicle (more for bus only)	Center axis of vehicle/Y Direction TBD		
F		Receiver coil must be compatible within power classes	TBD (Options 1-4)		
		Required tolerance primary coil to secondary coil misalignment	Lateral TBD (X,Y)		
		Communications/alignment	DSRC/RFID		
G		Vehicle category? Ground clearance (e.g., VDE M1=120mm)	M1, N1	M2, N2	M3, N3
H		Ground clearance tolerance	M1=Z +/-, TBD	TBD	TBD

SHE Issues for WPT Emissions and Exposures, and Applicable Safety Standards

SHE impacts of EMF and EMR can be explored from the emissions perspective (where there is an EMF/EMR transmitter) or from the absorption perspective (where a human or the environment is receiving the EMF/EMR). By limiting the former for operational safety, it is likely (though not assured) that neither adverse health nor environmental effects result in the latter since the exposure limits will be below those specified in regulations or standards. For SHE assurance, both the emissions of fields/radiation at the source and human exposures can and must be controlled. In general, it is both easier and more cost-effective to measure, control, limit, and verify RF source emissions compliance, than to control human receptor exposures. As discussed below, Threshold Limit Values (TLVs) for physical agents refer to source emissions levels, and compliance with standards for Maximum Permissible Exposures (MPE) ensures SHE for the public and workers exposure to RFR.

The Institute of Electrical and Electronics Engineers (IEEE) International Committee on Electromagnetic Safety developed the C95 family of voluntary consensus standards, which is recognized by ANSI. These consensus standards establish MPE limits to electric and magnetic time varying fields for humans exposed to EMR and EMF in both controlled (occupational) and uncontrolled (public) environments. These exposure safety standards provide sufficient safety margins to protect vulnerable individuals. They also standardize the measurement and computational models of RF and other electric, magnetic and EMF interactions with humans. Further, these consensus standards prescribe workplace and public safety programs.

The human exposure safety limits to RFR vary with frequency and are time averaged over 6 minutes or 30 minutes, since the mechanisms for RFR (electric or magnetic fields) interaction with biological systems also vary. Electric fields are easily shielded or deflected, but magnetic fields penetrate body tissues to different depths (the higher the frequency, the deeper the "skin depth") and are of greater concern to human safety and health. Potentially adverse bio-effects of RFR depend on the Effective Radiated Power and the distance from the source; they include hearing clicks, seeing phosphenes (light flashes), tissue heating (thermal effects), neural stimulation, and contact shock and burns when touching nearby metal objects.

Because the WPT frequency chosen by the new SAE J2954 TF is below 100 kHz, the ANSI/IEEE human exposure safety standards for this frequency range applicable in the U.S.[113] are:

- IEEE C95.1™-2005 – Safety Levels with Respect to Human Exposure to RF EMFs, 3 kHz to 300 GHz
- C95.3.1™-2010 – Measurements & Computations of Electric, Magnetic, and EMFs with Respect to Human Exposure to Such Fields, 0 HZ to 100 kHz
- IEEE C95.7™-2005 – RF Safety Programs – 3 kHz to 300 GHz

There are corresponding, but different, human exposure RF safety standards and Basic Restrictions applicable abroad that were updated by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 2010, and endorsed by the World Health Organization (WHO).[114] For more than two decades the WHO has investigated the human exposure safety issues to RFR and defined and undertaken the R&D agenda, with U.S. participation. ICNIRP/WHO and IEEE are trying to harmonize international and U.S. standards, which differ at present.[115]

The IEEE and ICNIRP or FCC MPE limits for human electric and magnetic fields exposures in the workplace (occupational or controlled environments) and public (uncontrolled environment) limit the RF energy deposition in the body. The Specific Absorption Ratio (SAR) dose metric for EM energy deposition (by mass or volume) is defined so as not to raise core (or organ, brain, limbs, etc.) temperature by more than 1 degree Celsius. The IEEE 1528-2013[116] recommended practice provides updated test protocols to measure the peak spatial-averaged SAR induced in a simplified head model by hand held cellphones and other transceivers, while C05.1-2005 provides SAR measurement and estimation techniques for limbs and whole body RF exposures as a function of frequency.

The IEEE SAR or power density MPEs are shown in Table 4-2 as they vary with frequency. SAR limits are averaged RF energy absorption in tissue (4W/Kg for limbs and 2 W/kg in head and trunk tissue). The FCC limit is more conservative (1.6 W/kg in 1 g tissue).

Table 4-2

IEEE C95.1-2005 Broadband RF Exposure Safety Power Density Occupational and Public Limits

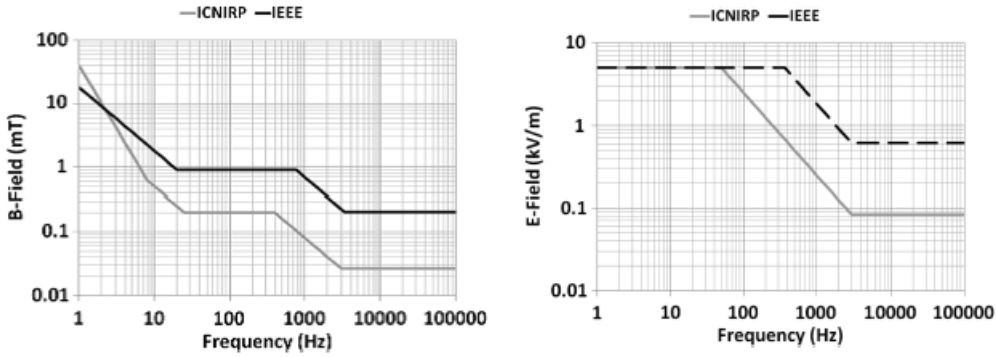
MPE Limits for Controlled Environments

Frequency (MHz)	Power Density (W/m²)
0.1–1.0	9,000
1.0–30	9,000/f²
30–300	10
300–3,000	f/30
3,000–300,000	100

Frequency (MHz)	Power Density (W/m²)
0.1–1.34	1,000
1.34–30	1,800/f²
30–400	2.0
400–2,000	f/200
2,000–100,000	10
100,000–300,000	Increases from 10 to 100

Figure 4-2

IEEE and ICNIRP Human Exposure Safety Limits for Magnetic Fields and Electric Fields[117]



The Occupational Safety and Health Administration (OSHA) RF exposure safety requirements for workers are based on IEEE consensus voluntary standards.[118] The American Conference of Governmental Industrial Hygienists (ACGIH)[119] posts TLVs and Biological Exposure Indices (BEI) for radiofrequency radiation, electric and magnetic fields as a function of frequency and duration of exposure to ensure workplace safety. These occupational limits would apply to bus drivers and maintenance workers at public transit agencies or commercial operators. Occupational TLVs are typically higher by a factor of 5-10 than public and environmental exposure limits, due to worker training and hazard awareness (in "controlled environments"), although they do provide a sufficient safety factor.

The FCC has regulations on human exposure safety to EMR/EMF from 1996, which are dated and currently being revised,[120] as well as guidance on how to comply with FCC regulations for licensed transmitters, or for ISM RF devices.[121] The FCC is currently considering specific rulemaking and spectrum allocation for wireless charging pads in automotive and consumer applications[122] and is participating in the SAE standards development effort discussed above.

An important health and safety consideration is prevention of harmful EMI with sensitive implanted or body-worn medical electronic devices (e.g., pacemakers, defibrillators, infusion pumps, hearing aids, pain controllers, wheelchairs). Another special safety concern is to protect sensitive or vulnerable population segments (older adults, children, pregnant women, and wearers of electronic devices) from potentially harmful exposures to both environmental or workplace EMF and EMR. The Center for Devices and Radiation Health, a part of the Centers for Disease Control and Prevention, provides regulations and guidance to medical device manufacturers for ensuring the medical devices immunity to EMI.[123]

Measured WPT Magnetic Fields for Buses Comply with Safety Standards

Most WPT providers have carefully measured EM (especially the magnetic) fields in the near-field off the ground WPT transmitter pad and inside the vehicle while charging, to ensure human exposure safety, as well as the operational safety of nearby equipment. The latter safety issue is called electromagnetic compatibility–EMC, or immunity to EMI. The magnetic field unit in the tables below is the microTesla (1 Tesla = 10,000 Gauss; for comparison, Earth's slowly varying magnetic field is about 0.5-1 Gauss, or < 100 microTesla).

For instance, in the 2012 FTA report 0028[124] the CETE/UTC researchers measured magnetic flux emissions for the wirelessly charged CARTA electric shuttle using the Conductix-Wampfler technology, both inside and outside the bus while it was charging at maximum power. In order to verify that public safety is assured through compliance with the international ICNIRP standard, the CARTA shuttle IPT charging EMF emission levels outside the bus (Figure 4-3, top left) and inside the bus (Figure 4-3, top right) were measured and shown in green to be below the ICNIRP EMF public exposure safety limits (Figure 4-3, bottom).

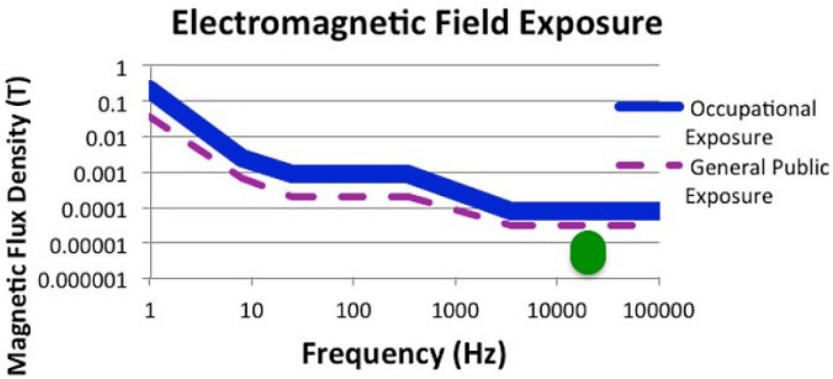
The Electric Power Research Institute (EPRI), member utilities, and RF safety experts have also undertaken comparative measurements of electric and magnetic fields near/in electric and hybrid electric vehicles and charging infrastructure (EVSE) versus conventional vehicles, including the CARTA electric shuttle bus equipped with WPT.[125]

The RF magnetic fields for WPT bus systems measured to date were reported to be well below ICNIRP and/or IEEE human exposure safety standards. However, the leakage fields must be managed, as done for the OLEV SMFIR, where vertical shielding is needed for the charger pad, and bus floor shielding is needed as well. KAIST researchers investigated the effectiveness of several magnetic field shielding materials at 20 KHz, and found that copper and aluminum plates performed better than ferrite or magnetic steel.

IPT Technology GmbH provided a report[126] documenting measurement results of magnetic fields as a function of distance from the charging and receptor coils, both at the roadside charging station, and outside the bus (for offsets of 5-9 cm, and for transmitted power of 60 kW). In all cases, the maximum magnetic flux density measured was in compliance with and below applicable international and national EMF human exposure safety limits, including those of U.S. (IEEE and ACGIH), ICNIRP, Canada, Australia, and German standards. The safety of wearers of active medical implants was also verified.

Figure 4-3

EMF Emission Levels[127]



Position	Flux Range
Forward of front wheels	<0.5 μT
Driver's side, between wheels	2.3–7.2 μT
Door side, between wheels	7.2–7.5 μT
Behind rear wheels	<0.5 μT
Background	0.13 μT
Inside bus at floor level directly above coils	4.1 μT
Inside bus 3 ft above floor directly above coils	0.41 μT
Inside bus 6 ft above floor directly above coils	0.21 μT
Inside bus at all other locations	<0.2 μT

The OLEV references cited in Section 2 indicate that both active shielding of roadway primary fields and passive magnetic shielding in the bus floor chassis is used to ensure compliance with the international ICNIRP human exposure safety limits for magnetic fields (62.5 milligauss at 20 kHz). As mentioned above, KAIST researchers found that aluminum and copper plates provided good magnetic field shielding at 20 kHz, but it is not known what the best magnetic field shielding materials are for vehicular WPT charging systems operating in the 85 kHz band recently adopted by the SAE J2954 standard, and if any of the providers have investigated field attenuation properties of various materials near/below 100 kHz.

WiTricity has measured and reported the RF magnetic field strengths at various locations where workers and the public might be exposed, and showed that modeled SAR does not exceed FCC regulations and the IEEE and ICNIRP safety standards.[128]

According to WAVE, their WPT buses have received a third-party certification for magnetic field safety with regards to both ICNIRP 2010 and ISO 14117.

INL has undertaken a systematic test and evaluation program of WPT commercial systems that includes both performance and safety evaluations. For instance, the EVATRAN Plugless Power system magnetic fields were measured

and evaluated by INL[129] as a function of distance from the transmitter and receiver coils (power pad) by INL and found to be safe (Table 4-3).

Table 4-3

Comparative SAR in FCC Regulations vs. ICNIRP Standard

	SAR (W/kg) (Whole Body Average)	SAR (W/kg) (Head/Trunk)	SAR (W/kg) (Limbs)	Induced E (V/m) (All Tissue)	Induced J (mA/m2) (Central Nervous System
FCC	0.08	1.6 (1 g)	4 (10 g)	–	–
ICNIRP 2010	0.08	2.0 (10 g)	4 (10 g)	$1.35 \times 10^4 f$ (f in Hz)	–
ICNIRP 1998	0.08	2.0 (10 g)	4 (10 g)	–	f/500 (f in Hz)

Standards for Electromagnetic Compatibility and Interference (EMC/EMI) and Operational WPT Safety Issues

There are numerous U.S. IEEE[130] and international vehicular EMC and EMI immunity standards[131] to ensure that inadvertent cross-talk among on-board digital electronics chips does not adversely affect the safe operability of on-board devices and ensure they are not susceptible to EMI from wayside transmitter. Inadvertent cross-talk among on-board digital electronics can be due to radiative, conductive, inductive, or capacitive coupling. The ISO 7637 family of automotive EMC/EMI standards (Road Vehicles Electrical Disturbances Package)[132] addresses the prevention and mitigation of electrical disturbances from conduction and coupling in motor vehicle equipment. It also specifies bench tests to determine the presence of, and measure electrical transients along supply lines, as well as methods for calculating the immunity of devices under test by coupling.

The European Committee for Electrotechnical Standardization (CENELEC) is implementing a 2004 European Union EMC Directive Electromagnetic Compatibility (EMC) Directive (2004/108/EC)[133] that concerns both EMI immunity and emission levels over the whole RF range.

Extensive EMI susceptibility testing and EMI protection is needed to ensure that emerging WPT bus battery recharging during either stationary or mobile operations do not affect the proper operation of other subsystems. For example, testing and protection is necessary to prevent a shutdown of, or other impairment to, the remote keyless entry subsystem or ignition subsystem. In the U.S. alone there are over 26 SAE EMC/EMI and more than 180 active, draft, and archived IEEE and ANSI EMC related standards.[134] Careful design and extensive EMC compliance[135] testing prior to deployment of WPT

systems is needed by providers, manufacturers and transit operators to ensure that either magnetic or capacitive EMI transient coupling from WPT operation does not adversely couple by radiation or induction to other electric traction power components or communications on the bus or nearby vehicles. For example, the converters, inverters, BMS, power control system, brake, crash avoidance and bag deployment signals all could become susceptible to this adverse coupling without careful design and testing. Crosstalk from WPT and among on-board electronics must be prevented, detected and suppressed for all transit bus or light rail operational scenarios. EMI susceptibility testing in the field is needed to determine if and which immunity countermeasures are necessary.

Another potential hazard is that EMI may induce high voltages and stray currents in nearby metal structures (e.g., fences, bridges, pipelines, metallic cars) and thus cause RF heating electric shock and/or burns to people touching them. Leakage magnetic fields could also magnetize metal tools or debris in roadways that could then become attached to the pavement or the bus, and obstruct WPT during charging. In an effort to prevent these effects, some providers are using debris and obstacle detection sensors as part of their WPT design. Stray induced voltages and ground currents from WPT buried in roadways or from wayside power supply equipment pose a known corrosion hazard to buried gas lines and electrical cables and transformers, which must be mitigated or prevented.

SECTION

5

WPT Technologies for Transit Applications: Status and Next Steps

Recent reviews of WPT technologies and their transportation applications[136] are optimistic about their prospects for deployment and growth. A promising strategy for competing WPT technology providers is to enter into partnerships with bus or LRV manufacturers in order to demonstrate in service operations, their commercial reliability, cost-effectiveness, and market niche viability. From this WPT review of emerging and existing transit applications in the U.S. and worldwide, it is evident that there are multiple candidate WPT technologies for transit applications in various stages of technology maturity: from development to prototype test/evaluation, to some in-service deployment.

Progress in WPT products standardization and the harmonization of international WPT standards will broaden market access to competing EVSE and on-board products for electric light duty and heavy duty vehicle applications, including public bus and rail transit as a market niche. WPT developers and technology providers claim multiple core benefits for EV owners and electric transit operators and users[137] that are yet to be proven in an operational environment, including:

- **Ease of use:** convenient choice of fast (dynamic) or slow (in station or depot) battery recharging with one infrastructure system; automatic trigger of charging when transmitter and receiver are coupled by an electronic "handshake"; the operator can't forget to plug in, or manipulate cords and plugs, or be exposed to adverse in order weather to recharge the battery.
- **Safety advantages:** high power transfer potentially in all weather, without corrosion or exposed terminals; no loose cords or potential for electrocution or tripping; no adverse human safety or health impacts (as long as emissions of and exposures to magnetic and electric fields and radiation comply with applicable guidelines, standards and regulations).

There are several active Federal agencies and partnerships efforts to demonstrate, evaluate, and improve WPT enabling technologies and products, as discussed at a DOE March 2012 Rapid Electric Vehicle Charging Workshop,[138] and shown by the DOE National Labs efforts cited above to test

and evaluate WPT products for safe operability. There are also ongoing DOT initiatives to evaluate the multimodal infrastructure implications of WPT, explored in:

- a workshop in November 2012 sponsored by the Research and Innovative Technology Administration (RITA, now part of the Office of Secretary of Transportation for Research and known as OST-R) and the Federal Highway Administration
- planning of stationary and mobile WPT charging infrastructure and electric connected vehicles discussed at workshops on ITS/Joint Program Office Applications for the Environment Real Time Information Systems (AERIS)[139]
- February 2013 Conference on Electric Roads and Vehicles Roundtables[140]

The ongoing FTA-funded electric bus pilot projects are expected to provide valuable information and lessons learned on both static and dynamic IPT infrastructure and electric vehicle system costs, reliability, safe operability and durability in various climates and duty cycles. Furthermore, the multiple and diverse transit WPT technologies and configurations described above must also be proven efficient, cost-effective, reliable and safe before their commercial deployment. Acceptance bus testing, such as the testing usually performed at FTA's Altoona, PA Test Facility, is also expected to provide consistent operational and environmental performance data to enable a comparison of emerging WPT bus technologies.

The DOE National Renewable Energy Lab (NREL) Technology Readiness Level (TRL) scale adopted for Fuel Cell Electric Buses commercialization readiness shown in Table 5-1[141] could also be adapted to WPT technologies as illustrated in Table 5-2.

Table 5-1

NREL TRL Scale Applicable to WPT Technologies

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Deployment (Stage 6)	TRL 9	Actual system operated over full range of expectations	Technology is in its final form. Deployment, marketing, and support begin for first fully commercial products.
Technology Demonstration/ Commissioning (Stage 5)	TRL 8	Actual system completed and qualified through test and demonstration	Last step in true system development. Demonstration of limited production of 50–100 buses at a small number of locations. Beginning transition of all maintenance to transit aff.
	TRL 7	Full-scale validation in relevant environment	Major step up from TRL 6 by adding larger number of buses and increasing hours of service. Full-scale demonstration and reliability testing of 5–10 buses at several locations. Manufacturers begin to train larger numbers of transit staff in operation and maintenance.
	TRL 6	Engineering/pilot-scale validation in relevant	First tests of prototype buses in actual transit service. Field testing and design shakedown of 1–2 prototypes. Manufacturers assist in operation and typically handle all maintenance. Begin to introduce transit staff to technology.
Technology Development (Stage 3–4)	TRL 5	Laboratory scale, similar system validation in relevant environment	Integrated system is tested in a laboratory under simulated conditions based on early modeling. System is integrated into an early prototype or mule platform for some on-road testing.
	TRL 4	Component and system validation in laboratory environment	Basic technological components integrated into system and begin laboratory testing and modeling of potential duty cycles.
Research to Prove Feasibility (Stage 2)	TRL 3	Analytical and experimental critical function and/or proof of concept	Active research into components and system integration needs. Investigate what requirements might be meet with existing commercial components.

Table 5-2

Summary of WPT Pilots[142]

	Application	Technology Specs	Demos	TRL
IPT Technology (former Conductix-Wampfler)	Electric Buses	IPT @15-20 kHz, 60 KW module in roadway, 30 kW modular onboard bus, < 1.5 in gap, >90% efficiency	CARTA, (Chattanooga, TN) electric shuttle; Turin and Genoa, Italy since 2002; Utrecht, Netherlands Utrecht since 2010; Lucerne, Switzerland; Lörrach, Germany; Rotorua, New Zealand.	Operational (TRL 8)
OLEV SMFIR	Electric bus and high capacity LRV	Bus: 20 kHz, 100 kW @85% eff., 20 cm gap Rail: 60 KHz	KAIST and Gumi, Korea, 2009-13	Operational for Bus (TRL 8); demo, T&E for rail (TRL 6-7)
WAVE	Electric buses	Prototype: 20 kHz, 25 kW,90% eff., several inch air gap for 22 ft. bus Plan: 50KW for 40 ft. bus (initial launch June 2014) & up to 140 KHz; higher powers also planned	USU, Logan, Utah; Long Beach, Monterey-Salinas Transit (MST); 2012-2014	Operational for electric shuttle, developmental for electric bus fleet at high power WPT (TRL 7-8)
Bombardier PRIMOVE	Electric buses and LRVs	Bus: 200 kW high power, for small gaps (No details)	Buses in Germany and Belgium, 2011-2013	Rail IPT was demonstrated in Augsburg (2010-12, TRL 8); bus IPT is operational (TRL 8)
EATON HyperCharger	Electric buses	200 kW, scalable to 1 MW. No other details	Released Dec 2013 for Europe electric buses. US targets: Tallahassee FL, Stockton CA, and Worcester MA	Developmental (TRL 7)

FCC licensing of WPT frequencies for public transit has not been finalized as yet, nor have updated FCC human and environmental exposure regulations been issued (public comments on an NPRM are currently being considered and addressed). The SAE J2954 85 kHz band that was just adopted in 2013 as standard frequency for vehicular WPT has not been used to date by any of the technology providers for commercial bus or rail WPT systems. Although compliance with this SAE industry standard is voluntary, it is likely that

most commercial developers and OEM integrators will have to modify their equipment and subsystems in order to comply. They will have to optimize power transfer control, efficiency and gap for this new standard WPT frequency in the US before achieving TRL levels required for deployment.

Other challenges to commercial WPT deployment yet to be addressed include:

- Understanding the total cost of ownership for competing WPT transit options relative to conventional or advanced alternatives, including infrastructure and vehicle capital costs, as well as operation and maintenance (O&M) and training.
- Ensuring the efficiency, reliability, and durability of power transfer under all weather conditions, including icing, snow (with plowing), mud, flooding, and temperature extremes.
- Providing for fault diagnostics, power control, and maintenance including easy access to both WPT infrastructure and vehicle modules.
- Obtaining operational data on competing WPT technology candidates which have yet to be proven in real transit marketplace as a practical, sustainable, safe, and energy efficient urban transit solution while also being reliable, maintainable, durable and which also offers lifecycle cost savings.
- Documenting the lifecycle, safety of operations, and maintenance for WPT infrastructure and on-board subsystems.

Information on the actual capital investment and the O&M lifecycle costs of various WPT technologies, broken down by subsystem (infrastructure and vehicle system) could not be found in the literature. Most of these emerging transit WPT systems were funded with front-end research, development and technology public or university funds, or subsidized by the developers. The economic issues for WPT's competing options, as well as their in-service reliability, availability and safety will become clearer over the next few years of bus or rail test and evaluation prior to large scale commercial deployment.

The energy efficiency of state-of-art commercial IPT systems[143] proposed for transit applications needs to be documented for in-service conditions and compared on a common basis. The OLEV bus operating in Gumi, South Korea is claimed to have achieved 100 kW power transfer at 20 KHz frequency (across a ground to vehicle gap of 20 cm) with up to 85% efficiency. The USU Aggie bus equipped with WAVE IPT technology was claimed to successfully transfer 25 kW dynamically at 90% efficiency at a 20 KHz frequency, but –as discussed above- future applications will explore WPT power transfer efficiency at both higher power levels and for higher frequencies (up to 140 KHz). IPT-Charge Technology has achieved opportunity charging efficiencies over 90% for small gaps (1.5 in) at 20 KHz,

using modular in-ground charge pads and bus receiver coils, over 12 years and several generations of deployed wirelessly charged buses.

Further research is needed to understand the cost-benefits and performance trade-offs of WPT options for in-service bus or rail transit systems, as summarized in Table 5-3.

Table 5-3

Summary of Transit WPT Research Issues and Needs

Summary of Transit WPT Research Issues and Needs	Safety	Environment	Health	Economic
Standardize WPT charging infrastructure (frequency, power) for interoperability	X	X	X	X
Standardize WPT subsystem onboard bus for cost-effective retrofit and integration with legacy vehicles	X	X	X	X
Develop acceptance testing protocols for WPT transit systems to verify safe operability, environmental compatibility, and compliance with applicable standards (SAE, IEEE) and regulations (FCC, DOT)	X	X		
Ensure workers and public health and safety for normal WPT system operations and for malfunction scenarios	X		X	
Use the FTA Safety Management System (SMS) and failure criticality analysis to compare WPT technology options	X			
Quantify and compare capital, operation and maintenance costs of WPT transit technology options using Lifecycle cost-benefit analysis (LCA)				X
Develop comparative data on WPT system reliability, availability, maintainability, safety, health and environmental impacts	X	X	X	X
Identify and develop Best Practices and Training for WPT system preventive maintenance and safe handling to ensure workers safety	X		X	
Determine how to prevent, respond to, or mitigate EMI or leakage EMF adverse impacts on human electronic implants and on wayside susceptible facilities	X	X	X	
Perform scenario analysis of WPT infrastructure vulnerability to damage from heavy traffic and extreme weather	X			X

Stepping stones to WPT deployment include the:

- Standardization and interoperability that could, for example, result in smaller electric and plug-in vehicles sharing the in-pavement IPT infrastructure with buses.
- Standardization of IPT subsystems for smooth and safe integration with legacy urban transit infrastructure and vehicles, so as to enable any bus platform to be retrofitted. This approach is needed for affordability and economies of scale.

- Development of WPT safe operability testing protocols consistent with SAE and UL industry voluntary standards.
- Documentation of compliance with existing FCC regulations and IEEE human exposure safety to RFR and magnetic fields.
- Ensuring that WPT technology that is already in service complies with applicable safety standards and regulations to protect the public and worker safety from normal WPT systems operation and from accidental malfunctions.
- Adopting the FTA Safety Management Systems approach by conducting a risk assessment for WPT equipped transit buses and infrastructure to provide fail-safe operational modes.
- Demonstrating that the capital, operating and maintenance costs of WPT infrastructure and vehicle subsystems (as well as associated RESS) are economically attractive, or make sense in terms of lifecycle benefits.
- Proving the durability of in-pavement primary charging pads, and reducing their vulnerability to damage from heavy urban traffic, weather extremes, thermal cycling, corrosive (winter salt) damage, snowplows, flooding and sorting of electrical components.
- Ensuring the availability of remote health monitoring and diagnostics of power supplies, WPT and RESS on-board components or safety-critical subsystems. Timely detection of degradation or component failures is needed for buried primary WPT coils and inverters which are inaccessible to inspection, as well as health diagnostics to ensure the proper operation of on-board secondary coils, inverters, cooling devices, power supply cables, and the WPT electronic communications and control devices.
- Developing of best practices for preventive maintenance and safe handling protocols for WPT bus and LRV deployment, as well as worker training. This would prevent electrical shock, contact burns, undue public, passengers or workers' exposures to EMR and fields, as well as potentially adverse EMI impacts on wayside facilities (ATMs, communication substations, hospitals, and handicapped wheelchairs or implants, and to on-board communications and control electronics).
- Assuring that the selected on-board batteries and RESS components (e.g., ultra capacitors) are appropriately selected (chemistry, capacity, lifecycle thermal properties) and have the energy storage capacity and power recharge/discharge characteristics without physical, electrical or chemical degradation from WPT rapid recharges.

Since there may be important inherent safety issues associated with different WPT technologies for both vehicles and infrastructure, a comparative Failure Mode and Effects Analysis (FMEA) and Hazard Analysis are needed to identify the safest architecture and operational options. Following this, acceptance testing of buses or LRVs recharged by IPT (static, or dynamic)

under real-service and for diverse environmental conditions is needed for operational safety assurance prior to widespread commercialization.

In order to address remaining challenges and speed up WPT commercialization and adoption by public transit authorities, FTA, transit agencies, commercial WPT technology providers, bus manufacturers and system integrators could collaborate in Public-private-partnerships (P3). The completion of ongoing TIGGER and Clean Fuels projects involving WPT demonstration and in-service evaluation of WPT bus applications will provide valuable insights and lessons learned going forward.

ENDNOTES

[1]See "Transit on cutting edge of clean technologies," APTA Policy Development and Research, Sept. 2012, at http://www.apta.com/resources/statistics/Documents/Transit-Clean-Technology.pdf; and "More than 35% of U.S. public transit buses use alternative fuels or hybrid technology: Public transportation is leading the way in green vehicles," Earth Day, 2013 at http://www.apta.com/mediacenter/pressreleases/2013/Pages/130422_Earth-Day.aspx.

[2]See "Advanced bus concepts: Perspectives from FTA programs," May 8, 2012, APTA presentation, Walter Kulyk, Director, FTA Office of Mobility Innovation, http://www.apta.com/mc/bus/presentations/Presentations/Advanced-Bus-Concepts.pdf.

[3]"Advancing transit fleets and technologies through TIGGER," Matthew Lesh, APTA 2012 Sustainability and Public Transportation Workshop, at http://www.apta.com/mc/sustainability/previous/2012/presentations/Presentations/Lesh,Matthew-Advancing-Transit-Fleets-and-Technologies-Through-TIGGER.pdf.

[4]See http://www.fta.dot.gov/grants_14835.html.

[5]See http://www.wirelesspowerconsortium.com/what-we-do/how-it-works/ and "Why not a wire: The case for wireless power" at http://www.wirelesspowerconsortium.com/data/downloadables/1/2/1/1/why-not-a-wire-the-case-for-wireless-power.pdf.

[6]See "Inductive Power Transfer systems (IPT) Fact Sheet: No. 1 – Basic Concepts" at

http://www.qualcomm.com/media/documents/inductive-power-transfer-systems-ipt-fact-sheet-no-1-basic-concepts.

[7]"Why not a wire: The case for wireless power," K. Siddabattula,TESLA Wireless Power Solutions, TEXAS INSTRUMENTS, at http://www.wirelesspowerconsortium.com/data/downloadables/1/2/1/1/why-not-a-wire-the-case-for-wireless-power.pdf.

[8]See "The convenience of wireless charging: It's just physics." White paper by Mark Estabrook, MediaTek at http://www.mediatek.com/_en/wp/wireless%20charging.pdf.

[9]See DOE "EV everywhere–a grand challenge in plug-in electric vehicles" at https://www1.eere.energy.gov/vehiclesandfuels/pdfs/ev_everywhere/ev_everywhere_initial_framing_doc_081512_final_2.pdf; and "Driving transportation to a cleaner future" at http://www.ksl.com/?sid=27588541.

[10]See Wireless Power Consortium technology at http://www.wirelesspowerconsortium.com/technology/basic-principle-of-inductive-power-transmission.html and Physics Central: Wirelessly charged electric buses" at http://www.physicscentral.com/explore/action/electric-bus.cfm.

[11]Source: www.physicscentral.com/explore/action/electric-bus.cfm.

[12]See postings at www.ipt-technology.com/index.php/en and at http://www.conductix.us/en/products/inductive-power-transfer-iptr.

[13]See electric mobility at http://www.youtube.com/watch?v=OIIIVT0eAZM&list=PLAFBDF9D200FAFED4&index=1.

[14]Source: http://www.wampfler.com/index.asp?id=10&plid=474&e1=2&e2=12&lang=E.

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[140]See http://cervconference.org/program/roundtables.

[141]See "Fuel cell buses in U.S. transit fleets: Current status 2012," Technical Report NREL/TP-5600-56406, November 2012, by L. Eudy, K. Chandler, and C. Gikakis, at http://www.nrel.gov/docs/fy13osti/56406.pdf.

[142]Adapted from http://www.eenews.net/stories/1059989839/print).

[143]See "Companies devise wireless charging for electric buses," WSJ blog, August 27, 2013, at http://blogs.wsj.com/digits/2013/08/27/companies-devise-wireless-charging-for-electric-buses/tab/print/.

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